Applications of Solid Lubricant Films in Spacecraft

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The use of solid (dry) lubricants, particularly solid lubricant thin films, in space systems, including satellites and launch vehicles, is reviewed. Various types of satellites and their generic mechanical requirements are outlined. Mechanisms that use solid lubricant films are described. The types of solid lubricant films available, including burnished, bonded, and sputter-deposited, are reviewed and their properties assessed relative to application requirements. Future opportunities for insertion of solid lubricants as replacements for liquid or grease lubricants are identified.

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PREFACE

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INTRODUCTION

Solid lubricant films are used in a variety of mechanisms on various spacecraft and launch vehicles. Relative to liquid lubricants, solid lubricants generally have lower vapor pressures, better boundary lubrication properties, insensitivity to radiation effects, and wider operational temperature ranges [1,2]. This paper reviews the use of solid (dry) lubricants, particularly solid lubricant thin films, in such space systems. Future opportunities for insertion of solid lubricants as replacements for liquids or greases are identified.

TYPES OF SPACECRAFT AND MECHANISMS

In broad terms, the spacecraft considered within the scope of this text can be categorized (Figure 1) as one of the following types: remote sensing (e.g., meteorological), communication, or navigation satellites. All of these spacecraft use mechanisms that must be effectively lubricated to meet mission requirements. In addition, the tribology of launch vehicle mechanisms is critical to the successful placement of spacecraft into proper orbit. Launch vehicles and spacecraft have various release mechanisms that permit the spacecraft to separate from the launch vehicle. Spacecraft also have deployment mechanisms that allow subsystems (e.g., antenna dishes, solar panels, etc.), which are often folded during launch to conserve volume, to be opened in orbit. These release or deployment mechanisms require a lubricant to provide low friction (torque) for a low number of cycles. (Even though a release mechanism generally operates only once in flight, the mechanism and its lubricant have to undergo multiple cycling [e.g., 10 to 100 operations] during preflight ground tests.) The lubricant cannot be a source of vapor phase contamination once the spacecraft is in orbit because release mechanisms are usually exposed. Lack of thermal control may require the lubricant to function in a wide temperature range. On externally exposed mechanisms, the lubricant must withstand exposure to radiation, electrons, protons, and O atoms — the nature and quantity of this flux is dependent upon the orbit. All of

COMMUNICATION

SLIP RINGS
SOLAR ARRAY DRIVE
REACTION WHEEL

SURVEILLANCE

MOMENTUM WHEEL
ANTENNA POINTING

METEOROLOGICAL

GIMBAL BEARINGS
SLIP RINGS
MOMENTUM WHEEL
SOLAR ARRAY

NAVIGATION

REACTION WHEELS
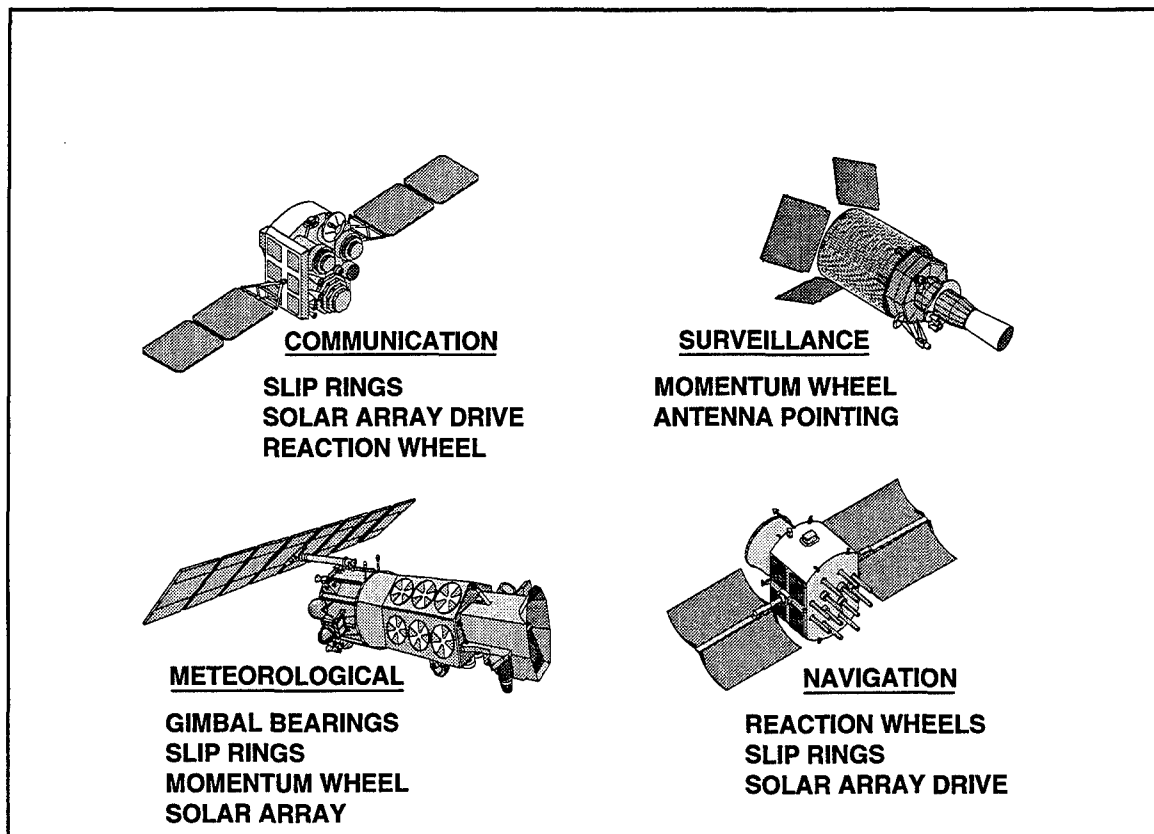SLIP RINGS
SOLAR ARRAY DRIVE

Figure 1. Types of satellites with list of generic mechanisms.

these requirements favor the use of solid lubricants, and indeed, release and deployment mechanisms are the largest application for solid lubricants in space systems.

In contrast, the long endurance, high cycle requirements of some spacecraft mechanisms usually necessitate the use of liquid lubricants, provided that potential contamination can be contained and that adequate thermal control is maintained, which keeps the liquid at proper viscosity. For example, the spin bearings in momentum transfer mechanisms ([MTMs], i.e., momentum and reaction wheels, and control moment gyroscopes) operate at high speeds with large duty cycles that necessitate liquid lubricants. However, there are other mechanisms on spacecraft in which either solid lubricants or liquid lubricants, with proper boundary additive packages, might be suitable, depending upon specific requirements. Design considerations in the selection of the proper lubricant include duty cycle/life, contamination (either evaporation into vapor phase or solid debris formation), moisture sensitivity of the lubricant during preflight storage, component tolerances, ease or robustness of lubrication application procedures, and cost [3]. Table 1 lists the relative merits of solid vs liquid lubricants.

Sensor or antenna pointing mechanisms usually are mounted on gimbal bearings. Such bearings are generally in boundary contact, which favors the use of a solid film lubricant. For optical sensors, minimization of vapor phase contamination also favors solid lubricants. However, the endurance and torque performance of the solid lubricant must adequately meet system requirements or a liquid lubricant will be selected. Friction and torque must remain steady throughout system life.

Sensors or antennas often must point or stare at an object for long periods of time. Consequently, the bearing balls have to dither over a small arc without ball overlap, and it is possible for the balls to push solid lubricant towards the end of the arc. When the mechanism is repositioned, torque bumps can be encountered, which can disrupt the feedback control software or even cause bearing seizure. For example, Figure 2 shows the formation and attenuation of torque

Table 1. Relative Merits of Solid and Liquid Lubricants for Use in Vacuum

Solid Lubricants	Liquid Lubricants
Negligible vapor pressure	Finite vapor pressures
Wide operating temperatures	Viscosity, creep, and vapor pressure are all temperature dependent
Negligible surface migration (Debris can float free)	Seals required
Accelerated testing possible (if wear mechanism verified to remain the same)	Accelerated testing invalid
Often sensitive to moisture exposure	Generally insensitive to air or vacuum
Friction is relatively independent of speed	Friction is speed dependent
Life determined by lubricant wear	Life determined by lubricant degradation
Poor thermal conductance	High thermal conductance
Electrically conductive	Electrically insulating

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bumps in an angular contact bearing lubricated with sputter-deposited MoS_2 as observed in our laboratory. The particular film shown has a columnar-plate morphology. Studies of other microstructures are in progress, but it is clear that film microstructure and film thickness must be optimized, and that appropriate "exercising" of the bearing can be periodically executed to minimize torque bump formation. During mechanism design, selection of bearings with large numbers of balls that will promote ball overlap on the raceways during rotation over a small arc will also minimize torque bump formation. Drive mechanisms on pointing mechanisms or solar arrays have similar design considerations (i.e., endurance and torque) when choosing between solid and liquid lubricants.
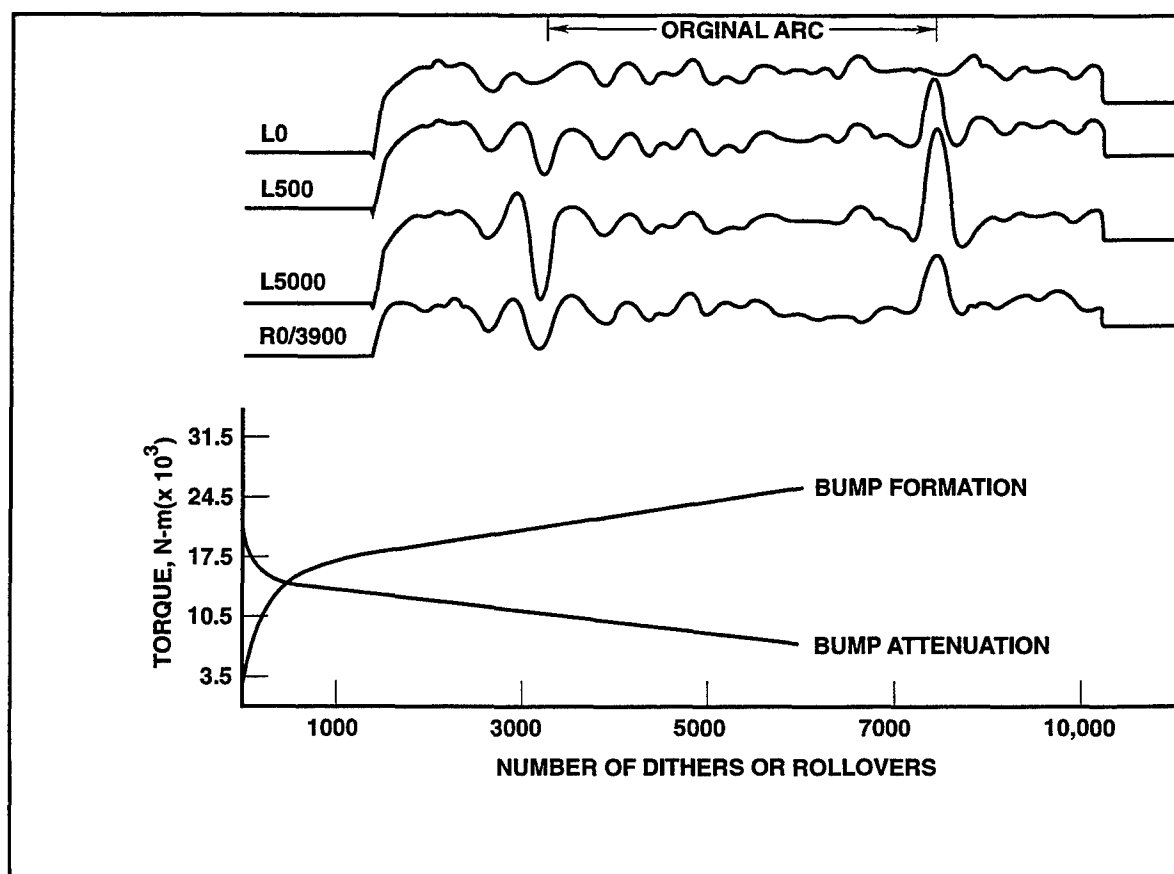
Figure 2. Torque data for oscillatory motion of angular contact bearings lubricated with a rf sputter-deposited MoS_2 film (1 μm thick) on the races. The 440C steel bearings have the following dimensions: ID ~ 30 mm; OD ~ 42 mm; Ball dia ~ 7 mm; 14 balls. The bearings were spring loaded to produce a hertzian stress of 0.56 GPa (70 ksi). (The film microstructure is represented in Figure 4 A). L0 is the initial torque trace; L500 after 500 oscillations; and L5000 after 5000 oscillations. An oscillation moves the inner race 8.4°, and a torque trace moves the inner race 16.9°. The negative and positive spikes correspond to the dropping into and rising out of depressions in the MoS_2 film formed by the balls during oscillation. RO/3900 is the torque trace after 3900 roll overs of the bumps and the trace shows the decrease in the amplitude of the torque bumps. The lower plots show the rates of formation and removal of the torque bumps as a function of the number of oscillations.

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Spacecraft often require lubrication across sliding electrical contacts of some type. Some spacecraft are stabilized by spinning the main body while the antennas and sensors are despun to point at specific objects, such as a ground station. Signals have to be transmitted across a sliding electrical contact ring assembly (ECRA). Spacecraft that are stabilized by MTMs often have rotating solar panels and electrical power transferred by an ECRA. However, these ECRAs usually use electrically conductive solid lubricant composite blocks, as opposed to solid lubricant thin films.

Solid lubricant films are of three general types (Figure 3): burnished, bonded, or vacuum deposited. General descriptions of most solid (and liquid) lubricants available for space and vacuum applications can be found in a recently published ASM handbook [3]. Specific descriptions of the lubricants, together with conditions for use, can be found in the NASA handbook written by McMurtrey [4]. This reference is a comprehensive treatise that should be consulted before choosing a space lubricant.

Burnished films are applied by a rubbing process that transfers the lubricant onto the surface to be coated. The resulting film thickness, coverage, and adhesion are very dependent upon the substrate preparation and rubbing procedures, which are generally difficult to control and reproduce. Burnished films have relatively low endurance compared to other preparation methods because of poor adhesion. Another disadvantage of the rubbing approach is that lubricant transfer can be sporadic or uneven (nonuniform), yielding lubricant bumps or bare regions on the contacting surfaces [5]. For precision mechanisms, unacceptable torque noise can result. In some cases, burnishing followed by brushing to remove thick or loose MoS_2 can leave thin films that are acceptable.

Bonded films are a mixture of solid lubricant (usually a lamellar compound) with a binder and a solvent. The use of the binder results in better adhesion of the lubricant to the substrate, yielding longer endurance relative to burnished films. Mechano-chemical methods, including grit blasting
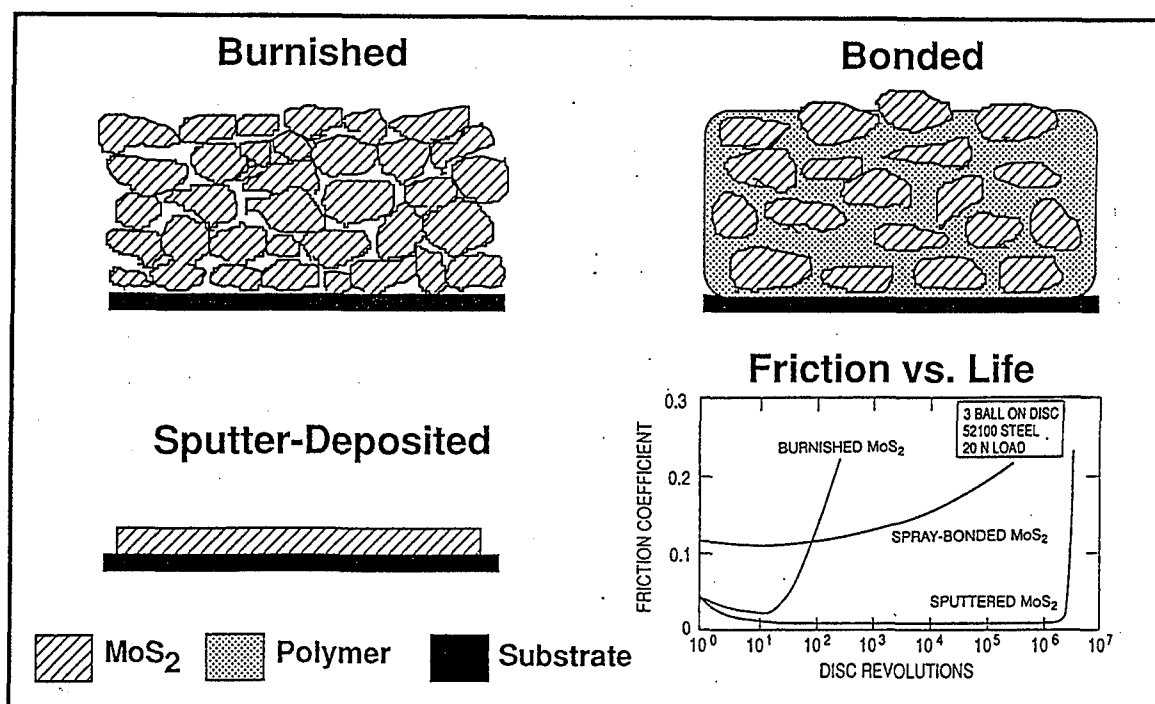

Figure 3. Cross-sectional illustrations of the different types of MoS_2 lubricants and a plot of their sliding friction values versus endurance. (The friction data is from Ref. 5.)

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and anodization of the substrate are often employed to improve film adhesion. The mixture is applied to the substrate by dipping, painting, or spraying, and the solvent is removed by either air or heat curing after application. Both inorganic and organic binders are available — the final selection is based on consideration of the load, temperature, and contamination requirements of the particular application [4]. Bonded films are generally several micrometers thick, which often does not allow for the lowest possible friction of low-shear materials, and which is dimensionally unsuitable (too thick) for many precision components. However, the bonded film technology is well established and is quite effective and appropriate for many low-cycle applications, such as release mechanisms, journals, clamps, etc., that cannot tolerate seizure [4].

Vacuum deposition techniques can be used to apply thin films of dry lubricants to obtain coatings with uniform coverage of components in precision systems. When film thickness is less than 1 μm, low and steady friction has been obtained [5]. For precision mechanisms, the films can be applied by sputtering [1, 6, 7], ion plating [8], or other ion-beam-assisted techniques [9, 10] to obtain even, controlled lubricant coverage. Ion cleaning prior to deposition can be used to improve film adhesion to components. Dopants can be added continually (to form alloyed films) or periodically (to form multilayer films) to modify film microstructure and performance [11, 12].

There are four types of solid or dry lubricants available for vacuum/space applications, including soft metals, lamellar solids, polymers, or other soft solids. Composites of these four types of lubricants or combinations of one or more of them with matrix or support materials are also available. Composites can be used to develop a source of lubricant resupply if some portion of the mechanism is fabricated from the lubricant. The lubricant transfers to other components by rubbing. For example, ball bearing cages (retainers) made of polymer-based composites or of leaded bronze have been used in this way [1]. ECRAs use composite blocks of silver, MoS_2, and either graphite or copper to provide lubrication and electrical conductivity simultaneously [13, 14].

The soft metals that have been used for vacuum applications include Pb, Au, Ag, and In. Of these metals, Pb has had the most success and use, though primarily on European spacecraft [1]. Pb films have not been used in many U.S. systems because older, competing, technologies have been adequate in meeting system requirements to date. Optimum performance of Pb and other metals is achieved at approximately 1 μm thickness. Deposition by ion plating provides excellent adhesion, and these films have been particularly effective in spacecraft bearings found in solar array drive mechanisms, especially in European satellites, and recently on the Hubble Space Telescope. A particular disadvantage of Pb is that it oxidizes rapidly and must be stored in vacuum/dry environments. Au and Ag are used in situations requiring electrical conductivity.

The lamellar compounds that can be used as lubricants include the disulfides and diselenides of Mo, W, Nb, and Ta. Graphite, which depends upon intercalates to expand the basal plane spacing that is essential for low shear and low friction, is not suitable as a lubricant in vacuum or space because intercalated water vapor normally present is removed below ~10^{-2} Pa (10^{-4} torr) [15, 16]. Intercalated graphite compounds have been developed that work well in vacuum, though they are not widely available and so far have only been applied by burnishing or in bonded films [17].

MoS_2 is the most widely used lamellar compound solid lubricant material for space applications. In burnished and bonded form, MoS_2 is used on many types of release and deployment mechanisms. As noted earlier, MoS_2 is used in composite blocks with Ag and graphite or Cu for sliding

electrical contacts. Sputter-deposited MoS_2 is used in release mechanisms, but the sputter-deposited form is particularly suited for precision bearing applications. Sputter-deposited MoS_2 has a lower coefficient of friction than ion-plated Pb (0.01 vs 0.1, respectively [5]), which means that MoS_2-coated components should develop less torque. This difference is important because power capacity is fixed on spacecraft, being supplied by solar cells and batteries.

Recent studies of sputter-deposited MoS_2 have been directed towards improving the film deposition technology for precision bearings [7, 10, 12, 18]. Structural studies of MoS_2 indicate that the microstructure results from heterogeneous nucleation and competitive growth between basal-plane and edge-plane oriented grains. In general, pure sputter-deposited MoS_2 films have a columnar plate morphology having edge-plane preferred orientation parallel to the surface (Figure 4A).

Substrate surface modification can increase the overall basal-plane preferred orientation near the substrate, but subsequent film growth defects generally cause edge-plane orientation to develop away from the interface. Studies by the authors have shown that edge-plane competitive growth
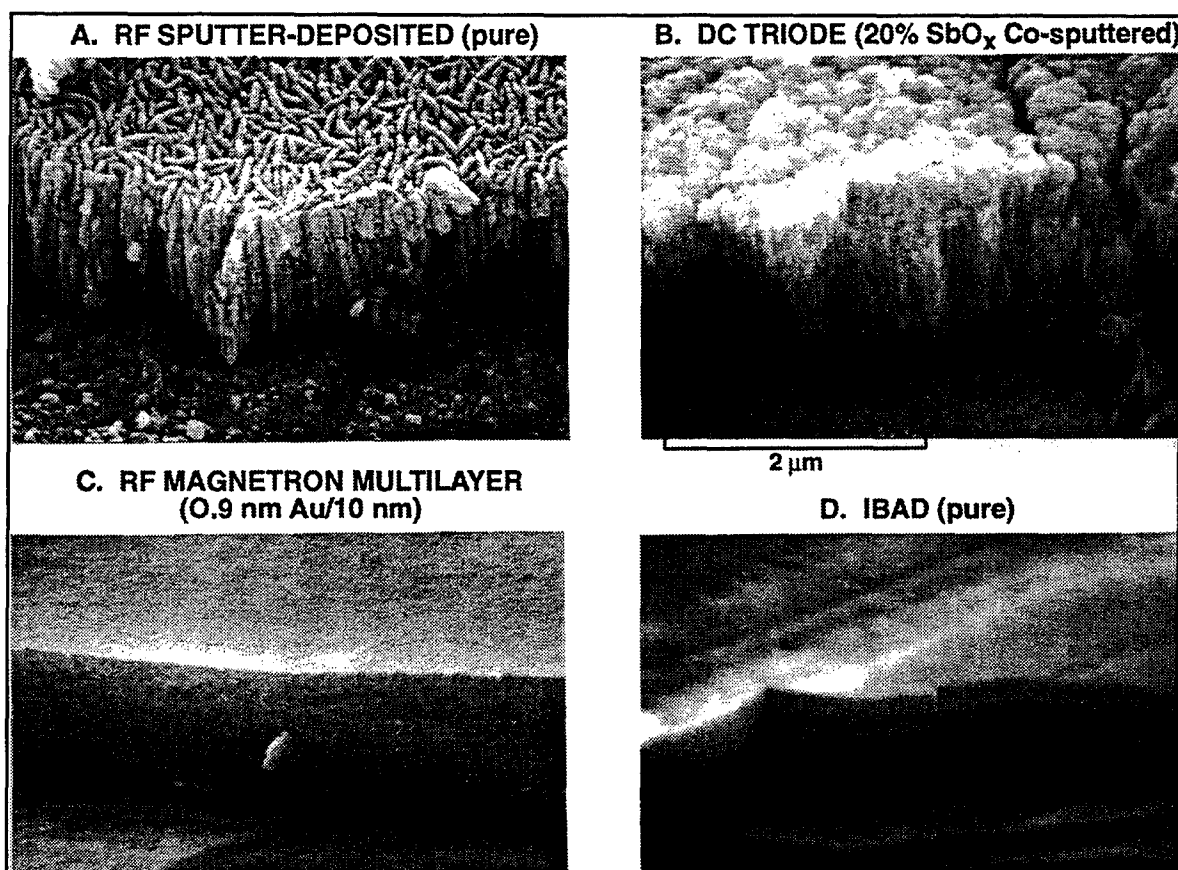
Figure 4. SEM micrographs showing the cross-sectional morphologies of various MoS_2 films, after brale indentation, prepared by (a) rf sputtering; (b) dc triode sputtering with 20% SbO_x codeposited; (c) rf magnetron sputtered MoS_2/Au-20%Pd multilayer films (the Au-20%Pd layers are 0.9 nm thick having a repeat periodicity of 10 nm); (d) IBAD (deposition was periodically modulated with increased sulfur, which appears to form steps during fracture). The pure, sputtered films have a porous microstructure and edge plane preferred orientation parallel to the surface. The torque data shown in Figure 2 were generated from a pure rf sputter-deposited film. The use of dopants, multilayers, or ion beams densifies film morphology and promotes basal-plane texturing as opposed to edge-pane texturing.

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can be suppressed by adding co-sputtered dopants (Figure 4B), yielding a fibrous morphology with no long-range order, or by incorporating metal multilayers (Figure 4C), yielding a dense morphology with strong basal-plane orientation. Figure 4D shows a sulfur-modulated MoS_2 film prepared by ion-beam-assisted deposition (IBAD). Concurrent ion bombardment during film growth suppressed edge orientation and yielded a dense morphology. Research into the performance (i.e., endurance and torque characteristics) of sputter-deposited MoS_2 in angular contact bearings designed to simulate precision gimballed systems is underway [18].

One particular disadvantage of sputter-deposited MoS_2 is that it easily oxidizes in humid environments to form MoO_3, which has significantly lower endurance. Therefore, MoS_2-coated components must be ground tested and stored in dry or vacuum environments prior to launch. Film microstructure can affect the rate of oxidation. Basal-plane preferred orientation and large grain size can inhibit humid storage oxidation [19, 20]. MoS_2-metal multilayer films have been prepared that have a high (often exclusive) basal-plane preferred orientation [12]. These films should have excellent moisture storage resistance because of their crystalline orientation, although this hypothesis has not yet been verified.

Polymers can provide low-friction surfaces in vacuum, provided that the constituent molecular chains align properly at the contacting surface. Polytetrafluoroethylene (PTFE) and some polyimides are the most widely used for space vacuum applications. Generally, additives are combined with these polymers to form composites in order to increase the load-bearing capability of the polymer material [2]. Mechanism components can be fabricated out of the composite, which provides a source of lubricant resupply to mating surfaces. Examples would include journal sleeves and bearing retainers (cages). When selecting a polymer for an application, it should be noted that PTFE tends to cold-flow more readily than the polyimides, but the latter are very moisture sensitive. Water molecules appear to hydrogen bond to the polyimide polymer molecules and then inhibit molecular shear. Thermal pretreatment of polyimides appears to be essential for good performance in vacuum [2].

EXAMPLES OF SOLID LUBRICANT APPLICATIONS

There are few reports in the literature on the use of solid lubricants in U.S. space systems mechanisms [21-23]. Table 2 is a list of some of the mechanisms that have used or are using MoS_2 solid lubricants, based on the authors' experiences at The Aerospace Corporation. Both bonded films and sputter-deposited films are used, though the former have been used more than the latter for release mechanisms. Sputter-deposited films tend to be used for precision mechanisms. Composites of MoS_2 with Ag and graphite are used in ECRAs (also known as slip rings).

Polymeric materials have been developed and are used for certain spacecraft applications [24]. Experimental work with specially designed retainers for solid lubricated bearings has been performed [25-26], and numerous retainer materials are available commercially [4].

Table 2. Uses of MoS_2 in Active Spacecraft

Device	Function	Comments	Film Type
Inertial properties measurement device	Provide attitude control	Requires constant, low friction multiple passes	Bonded
Launch clamp for primary sensor	Relieve launch load from bearings	Single point failure for primary mission	Bonded
Slip rings for microwave sensor	Transmit power, signal across rotating contact	Excessive noise degrades sensor performance	Composite
Solar array drive mechanism (SADM) bearings	Support for solar array drive despin mechanical assembly	Provides sun tracking for power	Bonded
Slip rings for SADM	Power and signal transfer	Noise sensitive for star tracker	Composite
Slip rings for SADM	Signal transfer	Noise sensitivity	Composite
Main weather sensor bearings	Scan for weather map	Torque bump sensitivity	Sputtered
Aft support bearings for orbiter interface	Provide pivot for launch from orbiter	Multiple environments, reuse	Bonded
Gimbal bearings, anti-backlash springs, jackscrews	Pivot and control for antennas	Sensitive pointing	Sputtered, bonded
SADM bearings	Support for solar array drive despin mechanical assembly	Low temperature operation	Sputtered, bonded
Gimbal springs, jackscrews, ball & sockets, gears	Control of motion, cradle release	Sensitive pointing	Sputtered, bonded
Bushings, springs, gears, clamps, etc.	Suspension, separation	Single point failures and wear points	Bonded, burnished
Alignment/Release Pins	Supports High Gain Antenna when folded	High friction prevents deployment, mission failure	Bonded

FUTURE INSERTION OPPORTUNITIES FOR SOLID LUBRICANT FILMS

As the properties of solid lubricant films become better understood and verified by research and testing, in conjunction with continual improvement of application procedures (e.g., process scale-up for large bearings), solid lubricants can be inserted confidently in place of liquid or grease lubricants. The most important impediment has been proving that solid lubricant films have adequate endurance for particular applications relative to the generally larger endurance of liquid and grease lubricants. The incentives for substitution are that solid lubricant films have negligible vapor pressures (eliminating the need for seals to prevent contamination) and can operate in wide temperature ranges. A consideration of all system requirements will be essential in selecting lubricants for future spacecraft that have increasing operational life requirements.

The deposition conditions necessary to produce dense, adherent coatings of MoS_2 by a variety of vapor deposition techniques (sputtering, IBAD) are now reasonably well understood. As testing on the endurance of these films in sliding and rolling element bearing configurations continues, a greater understanding of the endurance and torque performance of these coatings will result. Further studies are needed on the moisture storage sensitivity and solid debris generating characteristics of newer, dense MoS_2 films. If the MoS_2-metal multilayer films are found to have excellent storage resistance, they may replace bonded films in some release mechanism applications. Further testing is also needed on polymer composites, particularly for bearing retainer applications.

As a final point, hard ceramic coatings of TiN or TiC have significant potential for insertion on spacecraft bearings and gears using liquid lubricants and greases. Such coatings can reduce reactive degradation of such lubricants that can occur in boundary contact conditions. TiN has been shown to improve the endurance of fluorocarbon lubricants used in spacecraft mechanisms [27].

CONCLUSIONS

Solid lubricant films are used in a variety of mechanisms in U.S. spacecraft. Historically, their use has been confined to low-cycle applications. As research and testing has increased the understanding of the relationship between processing, microstructure, and mechanical testing performance, solid lubricants are increasingly replacing liquid lubricants in higher-precision, longer-cycle applications.

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